Overt and Covert Attention in Infants Revealed Using Steady-State Visually Evoked Potentials

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Although looking-time methods have long been used to measure infant attention and investigate aspects of cognitive development, steady-state visually evoked potential (SSVEP) measures may be more sensitive or practical in some contexts. Here, we demonstrate habituation of infants' SSVEP amplitudes to a flickering checkerboard stimulus, and recovery of attention upon presentation of a novel checkerboard stimulus. This modulation of SSVEP amplitude was more robust than the modulation of looking time. In addition, we provide evidence of enhanced SSVEPs in response to covertly attended checkerboards flickering in peripheral visual fields, even while infants are fixating a central stimulus. These experiments provide the first evidence of habituation and recovery of infant SSVEP amplitudes, as well as the first evidence of sustained infant covert attention using SSVEPs. SSVEPs may be a sensitive, efficient measure for use in studying early cognitive development, in particular infants' overt and covert attention.

Keywords: attention, SSVEP, infants, covert attention

Attention refers to how we select specific information arising either in our environments or in our bodies. William James (1890) wrote that attention "is the taking possession by the mind, in clear and vivid form, of one out of what may seem several simultaneously possible objects or trains of thought . . . It implies withdrawal from some things to deal effectively with others" (pp. 403–404). Although Titchener (1908) defined attention as the "increase of clearness for all objects in range," he also highlighted the importance of "lower level" attention, which includes processes that are not necessarily clear to the observer, but are important in perception and cognition (pp. 213–215). Specifically in visual processing, low-level attention involves alerting and orienting toward an object and the collection of information about its features by transducing light. Whereas higher level visual processing focuses on how these features are used to recognize objects, lower level attention includes a process of alerting and orienting to a stimulus

that is effortless and not necessarily voluntary. The first year of life is marked by significant developmental changes in both of these attentional processes.

Although visual fixation is primarily involuntary and reflexive in the first months of life (e.g., Johnson, Posner, & Rothbart, 1991), the development of the specific brain regions associated with voluntary control of eye movements, including the posterior parietal areas, pulvinar, and frontal eye-fields (i.e., the posterior orienting system), allow infants between 3 and 6 months of age to begin *voluntarily* fixating, disengaging, and shifting visual attention (Posner & Petersen, 1990). As a result, for over 50 years, researchers have used looking-time to examine the development of overt attention and other cognitive abilities in infants. Their studies have revealed that infants *habituate* to repeatedly presented stimuli—that is, their looking times decline with repeated stimulus presentations—and *recover* to baseline levels when they experience novel stimuli (Fagan, 1970; Fantz, 1964; Flom & Pick, 2012; Kavsek, 2012). The methods pioneered in these studies use visual fixations to assess infants' attention to stimuli and have been used to assess a range of cognitive abilities in infants including numerical skills (for review, see Christodoulou, Lac, & Moore, 2017), mental rotation skills (Moore & Johnson, 2008; 2011), and categorical processing of faces (for review, see Nelson & De Haan, 1997).

Studies measuring infant looking times across development also suggest that infants become more efficient at attending to and processing visual information in the first year of life (for reviews, see Colombo, 2001; Reynolds & Romano, 2016). Specifically, infants' peak looking times decrease from 3 to 6 months of age for a variety of stimuli including faces, geometric shapes, and images associated with Sesame Street (Courage, Reynolds, & Richards,

2006) and, compared to younger infants, older infants need less time to habituate (Freeseman, Colombo, & Coldren, 1993) and can recognize novel stimuli presented after longer delays (Diamond, 1990). Although these paradigms have been useful in investigating many aspects of cognition, they all depend on a behavioral measure of overt attention: looking time.

In contrast to this focus on overt attention, evidence from infant paradigms using either behavioral or event-related potential (ERP) methods suggests that infants may attend to certain information in the environment *without* exhibiting overt eye gazing toward the object; such attention is known as covert attention. Hood (1993) reported that eight 6-month-olds started head movements toward a side stimulus despite holding fixed gazes toward a central stimulus. Furthermore, Richards (2000) found evidence of covert attention in babies as young as 14 weeks using a spatial cuing procedure and scalp-recorded ERPs that were time-locked to saccades. In support of a covert shift of attention, infants' presaccadic ERPs were larger in response to the target when it was in the same location as the cue than when it was in an uncued location (Richards, 2000). Moreover, older, 20- and 26-week-old infants also showed inhibition of return, suggesting developmental changes in covert attending in the early months of life. These results suggest that eye gazing measures may not always reveal when infants are attending to a stimulus. Thus, studies measuring electrical activity in the brain may provide an opportunity to assess infant attention to a stimulus beyond what behavioral measures may capture.

Applying multiple different methodologies is important in studying psychological constructs, as varied approaches can minimize measurement biases and provide converging evidence for observed effects or identify alternative explanations. Colombo (2001) called on researchers to consider the developmental trajectories of attention when designing experiments aimed at assessing infant cognitive functioning. In addition, he concluded that the existence of "varieties of visual attention in infancy clearly implies that no one attentional task or measurement in infancy will account for large amounts of variance in the cognitive status" (p. 357). Over the last 30 years, advances in electrophysiological techniques have allowed researchers to study infant perceptual and cognitive development using noninvasive measures of brain activity, to make inferences about psychological activity (for review, see De Haan, 2013). These techniques have allowed for the study of the development of attention in infancy using electrophysiological measures that do not depend on behavior; such techniques include ERPs, electroencephalogram (EEG) frequency bands, and steady-state visually evoked potentials (SSVEPs).

The goal of the current research was to assess if SSVEPs may be useful in measuring infants' attention modulation not observable through behavioral methods. SSVEPs are continuous neural responses detectable over occipital (Ding, Sperling, & Srinivasan, 2006), parieto-occipital (Müller et al., 1998), and temporo-occipital (Robertson, Watamura, & Wilbourn, 2012) scalp areas, evoked by repetitive visual stimuli flashing at a particular frequency. When presented at rates between 3.5 Hz and 75 Hz (Ding et al., 2006), electrical activity in adult brains does not return to baseline after each flash; instead, the EEG shows a periodic response—an SSVEP—matching the frequency of the flickering stimuli. SSVEP paradigms offer advantages for investigating attention (Keil et al., 2003). SSVEPs yield excellent signal-to-noise

ratios (SNRs) because of the large number of responses recorded per unit of time (Haegerstrom-Portnoy, 1993); this makes it easy to factor out noise such as movement artifacts, by means of the fast Fourier transform (FFT; Müller et al., 1998), and permits robust identification of small differences in SSVEP amplitudes (Di Russo et al., 2007). Although amplitude assessments of SSVEPs have been used to assess visual selective attention in adults (Morgan, Hansen, & Hillyard, 1996; Toffanin, de Jong, Johnson, & Martens, 2009), little is known about the attentional modulation of SSVEPs in infants (Robertson et al., 2012).

SSVEPs are valuable in the study of selective attention because they can be specifically tagged to stimuli flashing at specific frequencies (Chen, Seth, Gally, & Edelman, 2003; Morgan et al., 1996; Pei, Pettet, & Norcia, 2002; Toffanin et al., 2009). Morgan and colleagues (1996) asked participants to attend to a letter/number sequence either on the left or right side of a computer screen and ignore a similar sequence presented simultaneously in the opposite location. The letter/number sequences were superimposed on small background squares flickering at 8.6 Hz in one visual field and 12 Hz in the other. SSVEPs were larger in amplitude when elicited by the flickering squares behind the attended sequence than by those behind the ignored sequence, serving as a putative index of attention to those stimuli (Morgan et al., 1996). Subsequent studies likewise demonstrated that SSVEP amplitudes are enlarged in response to attended flickering stimuli versus simultaneously presented but unattended flickering stimuli (Chen et al., 2003; Pei et al., 2002).

More recently, Toffanin and colleagues (2009) reported that SSVEP amplitudes are also sensitive to gradations of attention. In their study, the attention of adult participants was directed toward a stimulus on the left, a stimulus presented simultaneously on the right, or both stimuli; these stimuli flickered at different frequencies between 8 Hz and 23 Hz. Although the frequencies of the flickering stimuli did not influence the SSVEPs' amplitudes, these amplitudes were greatest during focused-attention, lower during divided-attention, and lowest in the ignored-attention condition. These results suggested that such frequency-tagging methodologies can be used to study attention.

Although SSVEP paradigms are useful in studying attention in adults (Chen et al., 2003; Morgan et al., 1996; Palomares, Ales, Wade, Cottereau, & Norcia, 2012; Pei et al., 2002; Toffanin et al., 2009), applications to studying infant attention are scarce (Robertson et al., 2012). Researchers have used infant SSVEPs to study lower level sensory processes (Gilmore, Hou, Pettet, & Norcia, 2007; Shirai et al., 2009; Sokol & Dobson, 1976), but only one study to date has investigated attentional modulation of SSVEPs in infants (Robertson et al., 2012). Robertson and colleagues presented infants with a toy duck that contained two implanted light-emitting diodes (LEDs) that flickered synchronously at 8 Hz at the center of the body and at the head. Increasing 12-week-olds' attention to the duck by rotating it back and forth for 2 s resulted in increased SSVEP amplitudes and increased phase locking of the SSVEP to the toy's flicker rate.

In another experiment, these researchers arranged three toys horizontally: one larger and centrally located duck containing LEDs that flickered at 12 Hz and two other ducks, on the left and right, respectively, containing LEDs that flickered at 8 Hz or 10 Hz, counterbalanced. Not only did SSVEP amplitudes increase for frequencies corresponding to fixated stimuli, but they also in-

creased for frequencies corresponding to an object 500 ms before infants shifted their gaze toward that object (Robertson et al., 2012). These findings support prior research indicating that infants can attend both overtly and covertly, that is, with or without visual fixation (Hood, 1993; Richards, 2000), and that SSVEPs may serve as useful indices of infants' overt and covert visual attention.

SSVEPs may provide converging evidence with looking times as a measure of infant attention, and may help address limitations of behavioral methods (e.g., difficulties associated with distinguishing fixation-with-attention vs. inattentive, "blank" staring). SSVEPs may also help reveal neurocognitive mechanisms underlying infant visual attention. Further, difficulties associated with measuring ERPs in infants, including alpha waves, infants' excessive movements, high attrition rates (Hoehl & Wahl, 2012; Stets, Stahl, & Reid, 2012), and the risk of statistical errors in oddball ERP paradigms (Thomas, Grice, Najm-Briscoe, & Miller, 2004), may be avoidable with SSVEP methods. The three experiments reported here validated the use of a covert attention SSVEP paradigm with 4-month-old infants.

Experiment 1

Experiments were approved by the Pitzer College Institutional Review Board for Human Participants (Institutional Review Board #2247) as well as by The State of California Committee for the Protection of Human Subjects (Protocol #14–01-1471). As a first step to assess if a frequency-tagging method could be used to study attention in infants, Experiment 1 investigated if SSVEP amplitudes are independent of stimulus frequencies. A checkerboard was centered on a digital display and flickered at one of four different frequencies.

Robertson and colleagues (2012) reported that 3-month-old infants generated detectable SSVEPs in response to 8- and 12-Hz flickering stimuli, so frequencies in this range were chosen for testing. Two additional frequencies outside of this range—6 Hz and 15 Hz—were also chosen, to explore possible limitations in the use of SSVEPs to study attention in early infancy. Consistent with prior evidence in infants (Robertson et al., 2012) and adults (Toffanin et al., 2009), flickering stimuli were expected to elicit SSVEPs at the same frequencies as the stimuli, but SSVEP amplitudes were not expected to vary as a function of flicker rate.

Method

Participants. Records of new births and mailing addresses were sent to the research team by the State of California. New parents in the San Gabriel Valley of Southern California were contacted by mail, and interested parents returned a postcard or responded via the Internet to indicate their desire to participate in the study. This recruitment method yielded a racially, ethnically, and socioeconomically diverse sample and was used for all subsequent experiments.

The final sample contained 20 full-term 4-month-old infants: 10 males (M_{age} = 120.30 days, SD = 9.64 days) and 10 females (M_{age} = 124.10 days, SD = 11.05 days). One additional female infant was observed but excluded from analysis because of fussiness and failure to complete the task.

Stimuli. Each stimulus was a phase reversal modulated 6 × 6 checkerboard centered on a 53-cm computer monitor with a gray 1.27-cm border on the top and bottom and a gray 6.35-cm border on the right and left sides. Each square of the checkerboard oscillated from black (RGB: 0, 0, 0) to white (RGB: 255, 255, 255) and back at a frequency of 6, 10, 12, or 15 Hz. E-Prime 2.9 was used to create and present each stimulus on the monitor, to time trials, and to store data.

Electrophysiological data acquisition. EEG data were recorded using Net Station 4.5.4 software, GES 300 hardware, and a 128-channel Hydrocel Geodesic Sensor Net, from Electrical Geodesics, Inc. (EGI; Eugene, OR). Electrode impedance was kept under 50 kΩ for the duration of recording. EEG was recorded continuously at a 500-Hz sampling rate, amplified with a gain of 10,000, and band-pass filtered with 12 db per octave cutoffs at 1 Hz and 100 Hz and a notch filter at 60 Hz (EGI). Offline continuous data were filtered (.03-Hz high-pass, 45-Hz low-pass) and segmented into 7,900-ms-long segments starting 100 ms after the onset of each stimulus (to account for the <100-ms delay between the experimenter's button press to begin stimulus presentation and the appearance of the stimuli on the screen in front of the infant). Because SSVEPs are detectable over parieto-occipital (e.g., Müller et al., 1998) and temporo-occipital (e.g., Robertson et al., 2012) scalp areas, data from 30 preselected electrodes in these areas were used for analysis.[1]

Procedure. The researcher described the study procedure to the infant-participant's parents, who completed informed-consent forms and an infant questionnaire. Next, one researcher placed the electrode net on the infant's head while another minimized fussiness by entertaining the infant with a puppet toy. Infants were tested sitting on a parent's lap, 136 cm from a 53-cm monitor. This procedure was used for all subsequent experiments.

An attention-getter (a video stimulus representing a rotating rubber duck, rattle, or baby face) was presented on the monitor prior to each flashing checkerboard. The trial began when the experimenter pressed a key to indicate that the attention-getter had drawn the infant's attention to the monitor (i.e., visual fixation), at which point the attention-getter was replaced with the flashing checkerboard. Each checkerboard stimulus was presented flickering at a single frequency for 8 s in a given trial, and the order of presentation of the four checkerboard stimuli (i.e., flickering at the four different frequencies) was counterbalanced in a block design. Each block consisted of the checkerboard flickering at each of the four stimulus frequencies, such that every infant saw each stimulus for 8 s in each block. All infants saw three blocks of trials; thus, each of the four checkerboard stimuli was presented three times during the experiment, totaling 24 s of presentation for each checkerboard frequency.

EEG data processing. SSVEP amplitude was calculated separately for each 7,900-ms EEG segment following the onset of each checkerboard. A Hanning window was applied to each analyzed segment to reduce spectral leakage caused by discontinuities in the original signal (see Cerna & Harvey, 2000, for more infor-

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[1] Using the 128-channel sensor Net from EGI described above, the following electrodes in the parieto-occipital and temporo-occipital scalp areas were chosen: 77–79, 85–87, 91–93, 95–98, and 100–101 (right hemisphere) and 51–53, 57–61, 63–67, 69, and 72 (left hemisphere).

mation). After applying the Hanning window, SSVEPs were calculated using the FFT implemented in MATLAB R2015a.[2]

SSVEP amplitude was defined as the EEG amplitude at the frequency of the flickering checkerboard stimulus (6, 10, 12, or 15 Hz) divided by the "expected" amplitude at each frequency; this division corrected for changes in baseline EEG amplitude (Müller et al., 1998; Robertson et al., 2012), and yielded a SNR. The expected amplitude at each frequency was calculated by averaging the amplitudes at the frequencies adjacent (± 0.5 Hz) to the flicker frequency. If the amplitude of the EEG signal increased from baseline, the quotient obtained by dividing the amplitude at the stimulus flicker frequency by the expected amplitude at that frequency would be greater than 1.0; a quotient of 1.0 or less occurred when a stimulus did not produce an SSVEP. The SSVEP amplitudes across all 30 electrodes preselected for analysis were averaged by frequency. For example, the SSVEP amplitude at 6 Hz was calculated by averaging the SSVEP amplitudes at 6 Hz from all 30 electrodes.

Results

The SSVEP SNRs generated at 6, 10, 12, and 15 Hz were analyzed to assess if these stimulus frequencies differentially influenced SSVEP SNRs; we utilized a repeated-measures analysis of variance (ANOVA) with flickering frequency (6, 10, 12, or 15 Hz) as a within-subjects factor. A main effect of flicker frequency approached statistical significance, $F = 2.398$, $p = .077$, $\eta_p^2 = .112$. All pairwise comparisons were tested between the SNRs of 6, 10, 12, and 15 Hz. The SNRs in response to the 15-Hz flickering stimulus ($M = 1.10$, $SD = 0.66$) were lower on average than the SNRs in response to the 12-Hz ($M = 1.81$, $SD = 1.06$) and 10-Hz ($M = 1.81$, $SD = 1.11$) flickering stimuli, $t(19) = -2.19$, $p = .041$, $d = -.73$, and $t(19) = -2.31$, $p = .032$, $d = -.61$, respectively. The remaining differences were not statistically significant, $ps > .10$.

Confidence that an SSVEP has occurred requires the SNR for each frequency to be reliably over 1.0. Thus, the above analyses were followed by four separate one sample t-tests that were used to determine if the SSVEP SNRs were significantly greater than the baseline magnitude of the EEG signal (i.e., an SNR of 1.0, no detectable signal). The SSVEP SNRs generated by the 6-Hz ($M = 1.43$, $SD = 0.85$), 10-Hz ($M = 1.81$, $SD = 1.08$), and 12-Hz ($M = 1.81$, $SD = 1.06$) stimuli were significantly larger than 1.0, $t(19) = 2.26$, $p = .036$, $d = 0.51$, $t(19) = 3.32$, $p = .004$, $d = 0.75$, and $t(19) = 3.43$, $p = .003$, $d = 0.76$, respectively. Analysis of individual infants' performances revealed that 16 of 20 infants displayed SSVEP SNRs above 1.0 in response to stimuli flickering at 6 Hz (binomial probability, $p = .012$) and at 10 Hz (binomial probability, $p = .012$). In response to the stimulus flickering at 12 Hz, 18 of 20 infants displayed SSVEP SNRs above 1.0 (binomial probability, $p < .001$). Thus, the checkerboards that flickered at 6, 10, and 12 Hz generated SNRs that increased significantly from the baseline EEG signal, indicating that SSVEPs occurred in response to those flickering stimuli.

However, the checkerboard that flickered at 15 Hz did not produce a strong enough signal beyond the baseline EEG signal to generate a detectable SSVEP response. The SSVEP SNRs generated by the 15 Hz stimulus ($M = 1.11$, $SD = 0.66$) were not

significantly different than 1.0, $t(19) = 0.74$, $p = .467$. Only 11 of 20 infants displayed SSVEP SNRs above 1.0 in response to this stimulus (binomial probability, $p > .05$). For the infants that generated SSVEPs in response to the stimulus flickering at 15 Hz, their SNRs ($M = 1.81$, $SD = 1.06$) were significantly larger than 1.0 on average, $t(10) = 1.55$, $p = .008$, $d = 0.76$. So, when the infants successfully generated SSVEPs in response to the 15-Hz stimulus, they did so reliably. However, for the infants who did not generate SSVEPs, the SNRs ($M = 0.58$, $SD = 0.28$) were significantly less than 1.0 on average, $t(8) = -4.52$, $p = .002$, $d = 2.07$.

Discussion

Experiment 1 assessed the magnitude of infants' SSVEP responses to the presented stimuli, and evaluated if the SSVEP SNRs were independent of frequency across the frequency-range tested. Such independence is necessary for a frequency-tagging method that seeks to measure infants' attention allocation as a function of differences in SSVEP SNRs. The finding that stimuli flickering at 6, 10, or 12 Hz generated SSVEP SNRs significantly greater than 1.0 indicates that these stimuli have potential utility in studies of SSVEPs in infants at the tested age. Furthermore, the finding that there were no significant differences in the *size* of the SNRs generated by these three stimulus frequencies suggests that within this range, SSVEP amplitude is independent of flicker frequency. Thus, the results of Experiment 1 support the use of a frequency-tagging method with 4-month-old infant populations, using stimuli flickering at 6, 10, and 12 Hz.

Infants generated SSVEPs in response to three out of four tested frequencies; the 15-Hz stimulus did not produce SSVEPs consistently. Although 15 Hz is sometimes used with adult research participants (e.g., Pastor, Artieda, Arbizu, Valencia, & Masdeu, 2003), evidence of infant SSVEPs at flicker frequencies above 12 Hz is scarce (Sokol, Moskowitz, & McCormack, 1992). Further, SSVEP amplitudes generally decrease as flicker frequencies increase across broad ranges of frequencies (Norcia, Appelbaum, Ales, Cottereau, & Rossion, 2015). As also happens in adults' SSVEP SNRs in response to faster stimuli, noise overwhelmed the signal produced by a 15 Hz flickering stimulus enough to hinder a reliable SSVEP response in half of our sample of infants.

In general, developmental research on spectral EEG activity suggests that infants and children have lower spectral boundaries for the corresponding frequency bands found in adults (i.e., adult δ [1–3 Hz], θ [4–7 Hz], α [8–12 Hz], β [13–30 Hz], and

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[2] The FFT mathematical transform assumes that the original signal is periodic, that is, a continuous signal with an integer number of periods; the FFT assumes the two endpoints of the waveform being analyzed are connected (Cerna & Harvey, 2000). Because of this assumption (which is false in most real EEG recording scenarios), FFT can introduce sharp transitions at the endpoints, resulting in artificial discontinuities and a smeared version of the actual spectrum. This "smearing" is a result of the artificial discontinuities in the signal that is undergoing FFT; it artificially widens the signal as power "leaks" from one frequency to other frequencies, giving rise to what is known as spectral leakage. In most cases, a Hanning window, or a mathematical function that is zero-valued outside of a chosen interval, can be applied to reduce spectral leakage (Cerna & Harvey, 2000). In other words, a Hanning window assigns zero values to the ends of the input data and gradually increases and decreases the signal values just after and just before these end points, respectively, to avoid discontinuities and therefore spectral leakage caused by the FFT.

γ [30–100 Hz]; Niemarkt et al., 2011; Saby & Marshall, 2012; Tierney, Gabard-Durnam, Vogel-Farley, Tager-Flusberg, & Nelson, 2012). In studies of adult attentional patterns using SSVEPs, frequencies in the α range (8–12 Hz) are the most commonly used, as they are easily observed using EEG, are affected by mental tasks, and are strongest at occipital sites (e.g., Morgan et al., 1996). Adult SSVEP amplitudes peak at about 10 Hz, and although higher frequencies generate SSVEPs, the signal becomes smaller (Regan, 1966) and thus less detectable amid noise. In contrast, developmental research on infant EEG frequency bands suggests that within the alpha range (which appears around 3 months of age), the frequencies that generate the largest amplitude signals change over time; peak amplitude is found at around 3–6 Hz initially but by 12 months of age, the greatest amplitude signals are for 6–7 Hz (e.g., Cuevas, Raj, & Bell, 2012; Saby & Marshall, 2012). Consistent with previous findings on the changes in infant spectral EEG activity over the first year of life (e.g., Niemarkt et al., 2011; Tierney et al., 2012), infant SSVEP signals may also show greater amplitude at lower frequencies than adults (i.e., at frequencies <12 Hz). Thus, in infants, detecting SSVEPs at 15 Hz may be possible but more difficult than at lower frequencies.

Nonetheless, the SSVEP SNRs measured at the three lower frequencies were similarly sized, regardless of frequency. These results extended adult findings (e.g., Toffanin et al., 2009) to infants, suggesting a consistency between the nature of SSVEP amplitudes in adults and infants. These findings support the use of frequency-tagging methodologies with infants.

Experiment 2

Before assessing the possible use of SSVEPs to measure covert attention in infants, we examined SSVEPs as an index of overt attention in infants. As supported by evidence of habituation in behavioral and electrophysiological studies (Fantz, 1964; Snyder & Keil, 2008), we assessed changes in SSVEP amplitudes in response to a repeatedly presented checkerboard flickering at 10 Hz. We predicted that SSVEP amplitudes would decrease with repeated presentations of this visual stimulus (i.e., habituation). Amplitudes were expected to return to prehabituation levels when habituated infants were presented with a novel checkerboard flickering at the same frequency. Any such novelty effect would be consistent with evidence from behavioral looking-time studies (e.g., Fagan, 1970; Flom & Pick, 2012).

Method

Participants. A power analysis was conducted to estimate the required sample size, given the effect size reported by Robertson and colleagues (2012). Based on their published statistics describing the change in SSVEP amplitude associated with a change in infant attention, the estimated effect size was $d = 0.81$, $p = .005$. G*Power was then used to estimate the necessary sample size needed for $d = 0.81$, two-tailed, α of 0.05 and power of 0.95. This calculation indicated that the sample size required for a study with two experimental groups would be $n = 10$, with five infants assigned to each of the two groups. Accordingly, the necessary sample size for the current study was $n = 20$, with five infants assigned to each of the four experimental groups. The final sample consisted of 13 male ($M_{age} = 117.15$ days, $SD = 7.82$ days) and

7 female ($M_{age} = 119.28$ days, $SD = 12.06$ days) full-term 4-month-olds. Data from two male infants were excluded due to technical malfunctions.

Stimuli. Two phase reversal modulated checkerboards (6 × 6 and 4 × 4) were used as stimuli. Each stimulus was presented, in different trials, centered on the same computer monitor used in Experiment 1. Both checkerboards were composed of squares that oscillated between black (RGB: 0, 0, 0) and white (RGB: 255, 255, 255) at a frequency of 10 Hz. E-Prime 2.9 was used to present stimuli, time trials, and store data.

Procedure and electrophysiological data acquisition. The same EEG data acquisition method was used as in Experiment 1. In addition, a trained experimenter, invisible to the infant and blind to the stimulus, observed the infant's behavior and used the computer's spacebar to initiate trials and record the duration of the infant's fixations of the checkerboard stimulus. All experimenters completed training that included live, simultaneous coding of infant looking behaviors until they obtained reliability scores over $r = .90$.

An attention-getter like that used in Experiment 1 was presented on the monitor prior to each flashing checkerboard, and the trial began when the experimenter pressed a key to indicate that the attention-getter had drawn the infant's fixation, at which point the attention-getter was replaced with the flashing checkerboard. Each trial was terminated either 2 s after the experimenter released the key to indicate that the infant was no longer fixating the stimulus, or after 60 s of looking, whichever came first. If the infant returned their attention to the checkerboard in the 2-s interval, the trial continued.

Infants were randomly assigned to either a 4 × 4 or a 6 × 6 checkerboard habituation group, such that in an initial series of identical habituation trials, they repeatedly saw the same habituation stimulus—either the 4 × 4 or the 6 × 6 checkerboard—flickering at 10 Hz. These two groups controlled for any different reactions infants might have had to these two stimuli. Habituation was determined using a moving average calculated across infants' most recent four trials. Each infant was considered habituated when his or her average time fixating the habituation stimulus declined in a given four-trial series to 50% of his or her average fixation time in the first four trials. Thus, each infant saw at least five habituation trials.

After reaching the habituation criterion (or after 12 habituation trials, whichever came first), each infant saw two test trials. Control-group infants saw the same checkerboard in the test trials that they saw in the habituation trials. Experimental-group infants saw a novel checkerboard in both of these trials (either the 4 × 4 or the 6 × 6 checkerboard, whichever they did not encounter during habituation). Test checkerboards were presented flickering at the same 10-Hz frequency as the habituation stimuli.

EEG data processing. The duration of each analyzed EEG segment varied in the current habituation paradigm because the length of each trial varied, depending on the infants' looking. However, a minimum of 2,000 ms of EEG data were needed per trial to obtain estimates of SSVEP amplitudes at 0.5-Hz intervals. SSVEP amplitudes were calculated separately for each segment following the onset of each checkerboard, using the FFT implemented in MATLAB R2015a. SSVEP amplitudes were defined as SNRs as in Experiment 1.

Results

The statistical analyses reported below assessed habituation and recovery of attention in the behavioral and electrophysiological data. The dependent measures included looking times at, and SSVEP SNRs generated by, the checkerboard stimuli. Although the infants saw two test trials, analyses using data from the second test trial revealed statistically insignificant effects; therefore, subsequent analyses included only first test trial data. In general, infants lost interest in the stimuli by the second test trial.

Behavioral results: Habituation. The number of trials required to produce habituation did not differ for the infants in the experimental and control groups, $t(18) = .66$, $p = .636$, $d = 0.22$. To test for habituation of looking, a 2 (Group: experimental vs. control) × 2 (Trial: first habituation trial vs. last habituation trial) mixed ANOVA was used. There was no main effect of group and no interaction of group and trial, meaning there were no significant looking time differences between the experimental and control groups at either the start or end of the habituation phase. A main effect of trial was found, $F(1, 18) = 22.64$, $p < .001$, $\eta_p^2 = .557$. A planned comparison t-test revealed that, as predicted, the infants habituated; there was a statistically significant decline in looking time from the first ($M = 21.64$, $SD = 13.92$) to the last ($M = 6.36$, $SD = 3.57$) habituation trial, $t(19) = 4.69$, $p < .001$, $d = 1.50$ (see Figure 1A).

Behavioral results: Novelty effect. The experimental group saw a novel stimulus in the test trial whereas the control group experienced a test trial in which they saw the same stimulus seen during habituation. Thus, differences in looking time patterns across the last habituation and test trials were predicted between the groups. Specifically, looking times for infants in the control group were not expected to differ between the last habituation trial and the test trial, because these infants continued to see the same stimulus across all trials. However, looking times for the infants in the experimental group were expected to increase from the last habituation trial to the test trial, because these infants saw a novel stimulus during the test trial. Further, no difference in looking times was predicted between the experimental and control groups during the last habituation trial, because both groups had identical experiences throughout the habituation trials. However, infants in the experimental group were expected to look at the novel stimulus they saw in the test trial longer than infants in the control group were expected to look at the familiar stimulus that *they* saw in the test trial.

To test for novelty effects in infants' looking times, a 2 (Group: experimental vs. control) × 2 (Trial: last habituation trial vs. test trial) mixed ANOVA was used. A within-subjects main effect of trial was found; on average, infants looked longer during the test trial ($M = 9.28$, $SD = 5.36$) than during the last habituation trial ($M = 6.36$, $SD = 3.57$) $F(1, 18) = 4.89$, $p = .04$, $\eta_p^2 = .214$ (see Figure 2A). Also, a main effect of group indicated that the looking times of the infants in the experimental group ($M = 9.38$, $SD = 6.08$) were greater than the looking times of the infants in the control group ($M = 6.26$, $SD = 1.97$), $F(1, 18) = 5.26$, $p = .034$, $\eta_p^2 = .226$. However, the predicted interaction between experimental group and trial was not significant, $F(18, 1) = 2.52$, $p = .137$, $\eta_p^2 = .119$.

Planned t-tests were used to evaluate the differences in looking times *within* the experimental and control groups across trials. For the experimental group, the difference in looking times between the last habituation trial ($M = 6.89$, $SD = 4.59$) and the test trial ($M = 11.87$, $SD = 6.56$) approached but did not reach the threshold of statistical significance, $t(9) = 1.92$, $p = .087$, $d = 0.88$. For the control group, the difference in looking times between the last habituation trial ($M = 5.83$, $SD = 2.27$) and the test trial ($M = 6.69$, $SD = 1.62$) was not significant, $t(9) = 1.72$, $p = .119$, $d = 0.41$.

Planned t-tests were also used to evaluate the differences in looking times *between* the experimental and control groups. As predicted, the experimental ($M = 6.89$, $SD = 4.59$) and control ($M = 5.82$, $SD = 2.27$) infants' looking times during the last habituation trial were not significantly different $t(18) = 0.66$, $p = .519$, $d = 0.31$. Likewise, as predicted, the experimental infants' looking times at the novel checkerboard during the test trial ($M = 11.87$, $SD = 6.56$) were significantly longer than control infants' looking times at the familiar checkerboard during the test trial ($M = 6.69$, $SD = 1.62$), $t(18) = 2.42$, $p = .026$, $d = 1.08$.

Electrophysiological results: Habituation. About 71% of the trials for all infants yielded SSVEPs; in the other trials, the flickering checkerboard did not produce a strong enough signal beyond the baseline EEG to generate a detectable SSVEP (i.e., the SNRs were < 1.0). The differences in the average number of SSVEP-yielding habituation and test trials, respectively, provided by the experimental group (habituation: $M = 6.70$, $SD = 2.58$; test: $M = 1.60$, $SD = 0.52$) and the control group (habituation: $M = 6.20$, $SD = 1.55$; test: $M = 1.50$, $SD = 0.53$) were not statistically significant, habituation: $t(18) = -0.53$, $p = .606$, $d = 0.237$; test: $t(18) = -0.43$, $p = .673$, $d = 0.19$.
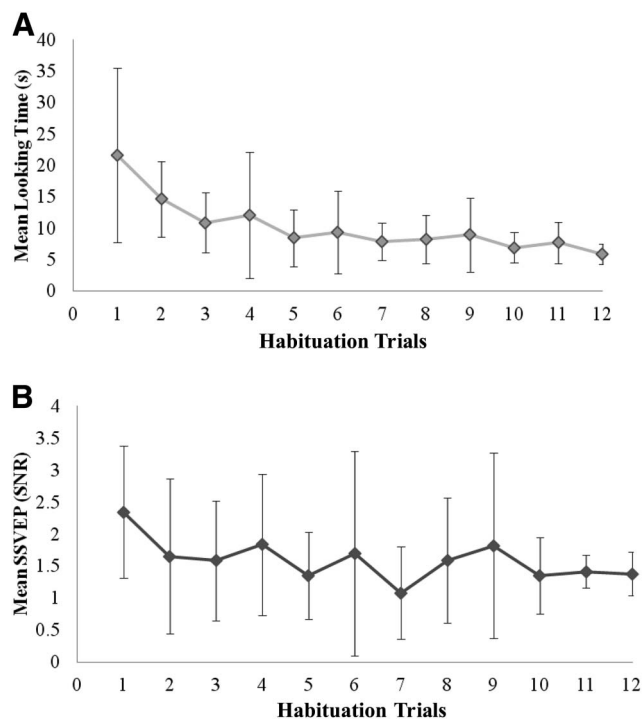

Figure 1. Pattern of mean (A) looking times (in seconds) and (B) steady-state visually evoked potential (SSVEPs; SNRs) across habituation trials.
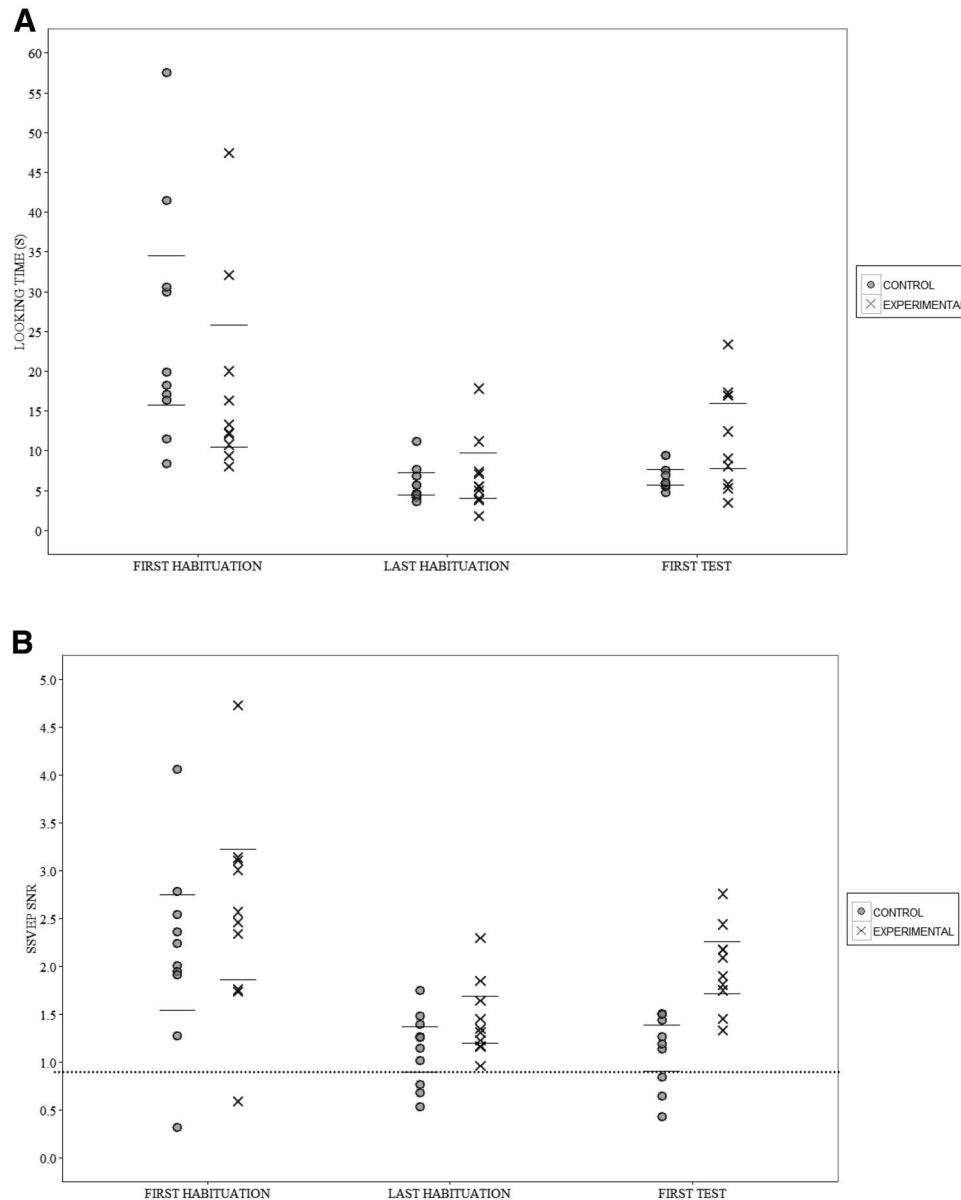
A

B

Figure 2. (A) Looking times (in seconds) and 95% confidence intervals (horizontal bars) for the first habituation, last habituation, and first test trials by experimental group in Experiment 2. (B) Steady-state visually evoked potential (SSVEP) signal-to-noise ratios and 95% confidence intervals (horizontal bars) for the first habituation, last habituation, and first test trials by experimental group in Experiment 2. The dotted line represents the SNR of 1.0 (an SNR of 1.0 or less occurred when a stimulus did not produce a steady-state visually evoked potential).

To test for habituation of SSVEP SNRs, a 2 (Group: experimental vs. control) $\times$ 2 (Trial: first habituation trial vs. last habituation trial) mixed ANOVA was used. There was no main effect of group and no interaction of group and trial, meaning there were no significant differences in SSVEP SNRs between the experimental and control groups at the start or end of the habituation phase. A main effect of trial was found, $F(2, 17) = 25.86$, $p < .001$, $\eta_p^2 = .589$. A planned comparison *t*-test revealed that, as predicted, the infants habituated; infants on average exhibited a significant decline in SSVEP SNRs from

the first ($M = 2.45$, $SD = 0.87$) to the last ($M = 1.33$, $SD = 0.44$) habituation trial, $t(19) = 5.21$, $p < .001$, $d = 1.62$ (see Figure 1B).

Electrophysiological results: Novelty effect. The experimental group saw a novel stimulus in the test trial whereas the control group saw the same stimulus in the habituation and test trials, so a difference in the pattern of SSVEP SNRs across the last habituation and test trials was predicted between the groups. Specifically, the same pattern of results was predicted for SNRs as was predicted for looking times.

To test for novelty effects in infants' SSVEP SNRs, a 2 (Group: experimental vs. control) $\times$ 2 (Trial: last habituation trial vs. test trial) mixed ANOVA was used. A main effect of trial indicated that on average, infants experienced a marginal increase in SSVEP SNRs from the last habituation trial ($M = 1.33$, $SD = 0.44$) to the test trial ($M = 1.57$, $SD = 0.59$), $F(1, 18) = 4.18$, $p = .056$, $\eta_p^2 = 0.188$. In addition, a main effect of group indicated that the SSVEP SNRs generated by the infants in the experimental group ($M = 1.72$, $SD = 0.49$) were greater than the SSVEP SNRs generated by the infants in the control group ($M = 1.18$, $SD = 0.42$), $F(1, 18) = 13.23$, $p = .002$, $\eta_p^2 = 0.425$. However, these main effects were qualified by the predicted interaction between group and trial, $F(1, 18) = 6.74$, $p = .018$, $\eta_p^2 = 0.272$.

Planned t-tests conducted to assess the differences between the means contributing to this significant interaction revealed that the experimental infants exhibited a novelty effect; that is, their SSVEP SNRs increased significantly from the last habituation trial ($M = 1.44$, $SD = 0.39$) to the test trial ($M = 1.99$, $SD = 0.44$), $t(9) = 4.73$, $p = .001$, $d = 1.31$. Further, the data revealed a return to prehabituation levels for the experimental group; that is, experimental infants' SSVEP SNRs increased in the test trial ($M = 1.99$, $SD = 0.44$) so that they were similar to prehabituation SNRs ($M = 2.55$, $SD = 1.09$), $t(9) = 1.87$, $p = .094$, $d = 0.57$. Control infants did not exhibit a novelty effect; the difference between their SSVEP SNRs in the last habituation trial ($M = 1.21$, $SD = 0.46$) and test trial ($M = 1.15$, $SD = 0.39$) was not significant, $t(9) = .316$, $p = .759$, $d = 0.04$.

As predicted, the experimental ($M = 1.44$, $SD = 0.39$) and control ($M = 1.21$, $SD = 0.46$) infants' SNRs during the last habituation trial were not significantly different, $t(18) = 1.19$, $p = .248$, $d = 0.54$. Likewise, as predicted, the SNRs generated in the test trial by the experimental group ($M = 1.99$, $SD = 0.44$) were greater than the SNRs generated in the test trial by the control group ($M = 1.15$, $SD = 0.39$), $t(18) = 4.58$, $p < .001$, $d = 2.05$ (see Figure 2B).[3]

Discussion

We believe this is the first study to detect habituation and recovery of SSVEPs in infants. As predicted, infants' SSVEP SNRs decreased significantly with repeated presentations of a stimulus and increased only with presentation of a novel stimulus, providing evidence for discrimination of these stimuli. Consistent with over 50 years of behavioral data on attention in infants (e.g., Fantz, 1964; Flom & Pick, 2012), the current study found habituation and recovery of infant electrophysiological activity, suggesting that SSVEPs can be used to detect changes in overt attention (Robertson et al., 2012).

The infants also habituated behaviorally, spending less time looking at the habituation stimulus over repeated presentations. However, the looking time data did not reveal a statistically significant novelty effect in the within-subjects analyses of the experimental infants' data. Despite this lack of statistical significance, the pattern of the looking time data was similar to the pattern of the SSVEP data, and the experimental infants did spend significantly more time looking at the novel test stimulus than the control infants spent looking at the familiar test stimulus. Taken together, these results suggest that compared to looking times,

SSVEPs may be more sensitive to overt attentional shifts in response to novel stimuli following habituation.

Experiment 3

A third study investigated how attention influences SSVEP amplitudes in infants, even in the absence of visual fixation. Because infants cannot be instructed to fixate or ignore specific objects, the current design used a dynamic, central video stimulus to attract infants' overt attention, while flickering checkerboards appeared simultaneously in their left and right peripheral visual fields. Specifically, visually compelling dynamic videos served as a central fixation point, while two black-and-white checkerboards (4×4 and 6×6) flickered in the right and left visual fields at different frequencies. Classic studies investigating infants' preferential looking found that 6×6 checkerboards elicit more overt attention (i.e., visual fixation) than 4×4 checkerboards (Ames & Silfen, 1965; Cohen, DeLoache, & Rissman, 1975; Karmel, 1969). Therefore, enhanced infant SSVEP amplitudes were predicted at the frequency of the 6×6 stimulus even while the infants were actively fixating the central video stimulus. These findings would be consistent with evidence in adults (Toffanin et al., 2009) suggesting that attention paid to a visual stimulus enhances the amplitude of the SSVEP, even in the absence of overt fixation.

Method

Participants. The final sample consisted of nine male ($M_{age} = 118.22$ days, $SD = 12.13$ days) and 11 female ($M_{age} = 121.18$ days, $SD = 12.52$ days) full-term 4-month-olds. Data from two infants were excluded, one male due to a technical malfunction and one female due to insufficient looking.

Stimuli. Three monitors were used for Experiment 3: one 53-cm monitor in the infant's left visual field, one 26-cm monitor centered in front of the infant, and another 53-cm monitor in the infant's right visual field. A compilation of dynamic scenes from three Baby Einstein (Burbank, CA) videos was presented on the center monitor; the purpose of this video was strictly to draw and hold the infant's overt attention. Two black-and-white flickering checkerboards (one 4×4 and one 6×6) were presented simultaneously on gray backgrounds, one on the left monitor and one on the right monitor, counterbalanced. Both checkerboards had a length and width of 13 cm and appeared on the furthest edge of the monitor (i.e., the left checkerboard appeared at the left edge of the left monitor, centered between the top and bottom edges; see Figure 3). Checkerboard complexity was independent of flicker frequency; that is, on any given trial, one of the checkerboards had squares that oscillated between black (RGB: 0, 0, 0) and white (RGB: 255, 255, 255) at one frequency (6 Hz or 10 Hz) whereas the other checkerboard had squares that oscillated between black and white at another frequency (10 Hz or 6 Hz, respectively). E-Prime 2.9 was used to present stimuli, time trials, and store data.

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[3] To address the possibility that SSVEP SNRs could increase or decrease systematically during a trial, a random sample of infants from the experimental and the control groups ($n = 8$) was selected, and these infants' SNRs in the first 2,000 ms of the test trial were compared to their SNRs in the entire test trial. Overall, there was no significant difference between the SNRs in the first 2,000 ms ($M = 1.52$, $SD = 1.17$) and in the entire test trial ($M = 1.57$, $SD = 0.33$), $t(7) = .14$, $p = .895$.
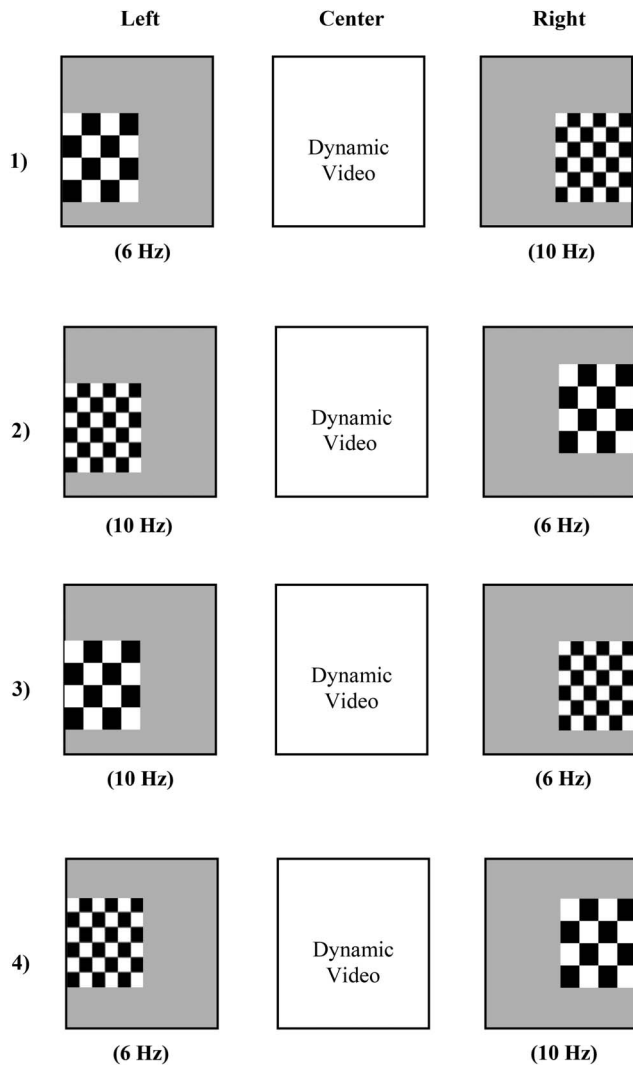
Left	Center	Right

Figure 3. The four stimulus pairs used, depicted in a sample order. Across trials, the checkerboard complexity (4 × 4 or 6 × 6), side of presentation (right or left monitor), and flickering frequency (6 Hz or 10 Hz) were counterbalanced in a block design. A 4 × 4 Latin square was used to counterbalance the order of the stimulus pairs presented across blocks, such that across the entire stimulus set presented to one infant, each pair was presented in each ordinal position only once.

Procedure and electrophysiological data acquisition. The same EEG data acquisition method was used as in Experiments 1 and 2. A trained experimenter, invisible to the infant and blind to the stimuli, observed the infant's behavior. This experimenter used the computer's "enter" key to initiate trials, and other keys to record the duration of the infant's fixations to the left, center, and right screens, respectively.

The dynamic Baby Einstein video was presented continuously on the center monitor throughout each trial. A trial began when the experimenter pressed "enter" to indicate that the dynamic video had drawn the infant's overt attention to the center monitor, at which point the right monitor began displaying either the more complex (6 × 6) or the less complex (4 × 4) checkerboard,

flickering at either 6 Hz or 10 Hz. Simultaneously, the left monitor began displaying the other checkerboard, flickering at the other frequency. In a given trial, one pair of checkerboards was presented for 8 s. Across trials, the checkerboards' complexity (4 × 4 or 6 × 6) and flicker frequency (6 Hz or 10 Hz) were counterbalanced across the left and right monitors in a block design. That is, there were four stimulus pairs presented, as depicted in Figure 3.

Each block consisted of four 8-s trials, and each trial within a block presented a different one of the four stimulus pairs; so, every infant saw each stimulus pair for 8 s in each block. All infants saw four blocks of trials; thus, each of the four stimulus pairs was presented four times during the experiment, totaling 32-s of presentation time for each pair. A 4 × 4 Latin square was used to counterbalance the order of the stimulus pairs presented across blocks, such that across the entire stimulus set presented to one infant, each pair was presented in each ordinal position only once.

EEG data processing. EEG data were segmented according to which monitor (center, right, or left) the infant was fixating at a given point in each trial; *only data collected while the infant was fixating the center monitor were analyzed*. The length of each segment varied because it was based on how long the infants looked at each monitor within each trial. However, a minimum of 2,000 ms of EEG data were needed per trial to obtain estimates of SSVEP amplitude at 0.5-Hz intervals. SSVEP amplitudes were defined as SNRs as in Experiments 1 and 2. SSVEP amplitude was calculated separately for each segment following the onset of looking at the dynamic, central video, using Hanning windows and FFT as in Experiments 1 and 2.

Because the checkerboards appeared in the infants' right and left visual fields, data from the electrode clusters in the parieto- and temporo-occipital scalp areas contralateral to the side of the stimulus were used for analysis (Robertson et al., 2012; Toffanin et al., 2009). Specifically, Toffanin and colleagues analyzed the strength of the SSVEPs from each electrode used in their study, and found the highest amplitudes originating from electrodes in the temporo-occipital area of the hemisphere opposite to the side of the stimulus presentation. Consistent with this approach, when an infant in the current study was looking at the central monitor and a 10-Hz checkerboard appeared in her left visual field, data from 15 preselected electrodes over the right hemisphere[4] were used to estimate the SSVEP amplitude at 10 Hz. In this example, the checkerboard shown simultaneously in the infant's right visual field was flickering at 6 Hz, so data from the 15 preselected electrodes over the left hemisphere were used to estimate the SSVEP amplitude at 6 Hz.

Results

A central aspect of the current design depended on the infants visually fixating the dynamic, center video. As predicted, the infants looked longer at the center stimulus ($M = 60.40$, $SD = 30.05$) both when compared to the left monitor ($M = 9.04$, $SD = 17.85$), $t(19) = 5.62$, $p < .001$, $d = 1.27$, and to the right monitor ($M = 7.86$, $SD = 9.05$), $t(19) = 6.74$, $p < .001$, $d = 1.60$. The difference between the infants' average looking time at the check-

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[4] As in Experiment 1, the preselected electrodes in the right hemisphere were 77–79, 85–87, 91–93, 95–98, and 100–101.

erboards on the right and left monitors was not statistically significant, $t(19) = 0.25$, $p = .804$, $d = 0.06$. Because infants in a given trial did not always look at the central video for at least 2,000 ms consecutively, SSVEP SNRs could not be calculated for 6.5% of the trials recorded. Only the data collected while the infants fixated on the center stimulus were used for the following analyses.

To compare the infants' SSVEP SNRs at the frequencies that corresponded to the stimuli flickering simultaneously in their left and right visual fields, we conducted a 2 (Checkerboard Complexity: 6 × 6 vs. 4 × 4) × 2 (Spatial Location: right vs. left visual field) × 2 (Flicker Frequency: 6 Hz vs. 10 Hz) repeated-measures ANOVA. As predicted, a main effect of checkerboard complexity was found such that the SSVEP SNRs driven by the more complex stimulus, the 6 × 6 checkerboard ($M = 1.14$, $SD = 0.22$), were significantly greater than the SNRs driven by the less complex stimulus, the 4 × 4 checkerboard ($M = 1.01$, $SD = 0.12$), $F(1, 15) = 6.76$, $p = .02$, $\eta_p^2 = 0.311$ (see Figure 4). The main effects of spatial location and flicker frequency were not statistically significant, $F(1, 15) = 3.58$, $p = .08$, $\eta_p^2 = .193$ and $F(1, 15) = 2.89$, $p = .11$, $\eta_p^2 = .161$, respectively. Likewise, neither of these factors significantly interacted with checkerboard complexity or each other in a way that significantly influenced SSVEP SNRs, $\eta_p^2 s < .02$.

Discussion

Experiment 3 provides the first evidence of sustained infant covert attention using SSVEPs. Extending Robertson and colleagues' (2012) finding that infant SSVEP amplitudes associated with particular stimuli increased immediately prior to gaze shifting toward those stimuli, SSVEP amplitudes in the current experiment increased during *sustained* covert attention. In the current experimental situation, infants looked mostly at the central video rather than at either of the two peripherally presented checkerboards. Prior behavioral research found that 6 × 6 checkerboards elicit more *overt* visual attention from young infants than do 4 × 4

checkerboards (Karmel, 1969), so 6 × 6 checkerboards are known to be more attractive to these infants than are 4 × 4 checkerboards. In the current study, significant elevations in infants' SSVEP SNRs were found for the more attractive checkerboard flickering in the periphery, even as the infants continued to fixate the central stimulus. Thus, the current results support the hypothesis that the observed enhancement of the SSVEP that was tagged to the more attractive checkerboard may reflect increased sustained, *covert* attention paid to this stimulus.

Although the design used by Toffanin and colleagues (2009) could not be replicated given the limitations of working with an infant population, the current results support their hypothesis that changes in SSVEP amplitudes may indicate neural modulation of attention. Consistent with this hypothesis and with Robertson and colleagues' (2012) results, the current results suggest that SSVEPs may be useful in understanding infants' attentional processing of visible objects, processing that is not evident using eye-tracking. These results also provide converging evidence of covert attention in infants, supporting previous behavioral (Hood, 1993) and ERP (Richards, 2000) studies and validating the use of SSVEPs as an indicator of infant covert attention.

General Discussion

Diversity and efficiency in approaches to measuring attention allocation are especially important for infant research that uses attentional patterns to study the development of various cognitive processes. The current studies validated a novel and sensitive tool to measure both overt and sustained covert attention in infants: SSVEPs in habituation and frequency-tagging paradigms. In Experiment 1, we established that infants' SSVEP amplitudes are independent of frequency between 6 and 12 Hz, thereby supporting the potential of frequency-tagging methods for studying attention in infants. Independence of SSVEP amplitudes and frequencies is a prerequisite condition for the use of such methods. In Experiment 2, different sources of data—both behavioral (looking times) and
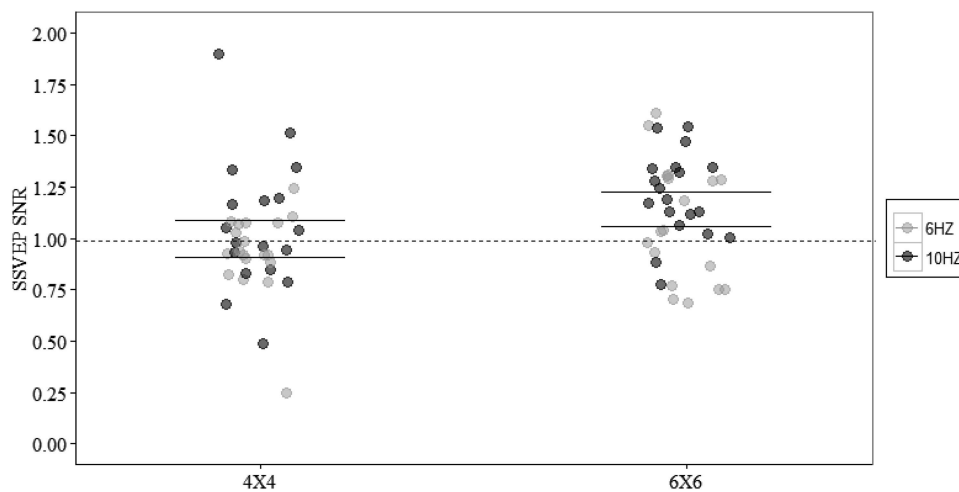

Figure 4. Steady-state visually evoked potential (SSVEP) signal-to-noise ratios and 95% confidence intervals (horizontal bars) for the 6 × 6 and 4 × 4 checkerboards by frequency in Experiment 3. The dotted line represents the signal-to-noise ratio (SNR) of 1.0 (a quotient of 1.0 or less occurred when a stimulus did not produce an SSVEP).

electrophysiological (SSVEPs)—converged to measure attention; looking times and SSVEP SNRs produced similar patterns of results. In Experiment 3, the results extended the use of frequency-tagging from adults (e.g., Toffanin et al., 2009) to infants, and validated a novel measure of attention that does not require any behavioral feedback. These results also support future work to examine other physiological measures (e.g., heart rate changes or blood-oxygen-level-dependent signals produced in functional MRI or functional near-infrared spectroscopy imaging) that may correlate with SSVEP SNR changes in response to infants' modulations of their attention. Measuring different types of physiological responses may be useful in studying the development of infant attentional patterns, especially in the absence of visual fixations or in cases when looking does not necessarily represent attending.

In Experiment 2, we assessed changes in infant SSVEP responses that may be related to overt attention. For decades, infant looking behavior has served as the primary method for measuring infant attention (e.g., Fagan, 1970; Sirois & Mareschal, 2004). Specifically, the pattern of infant looking associated with habituation and recovery of attention has enabled researchers to explore many aspects of infant cognition (e.g., Moore & Johnson, 2008; Nelson & De Haan, 1997). Consistent with the pattern of looking times typically produced in these paradigms, infant SSVEP SNRs in the current Experiment 2 decreased during habituation, and then recovered to prehabituation levels during presentation of a novel stimulus. Given this consistency with prior behavioral data, we believe these findings validated the use of SSVEPs as a novel measure of overt infant attention. Moreover, because our SSVEP data revealed a statistically significant interaction between trial and group whereas our behavioral data did not, the current results suggest that SSVEPs may be more sensitive to overt attentional shifts than are looking times. Thus, the current habituation paradigm using SSVEP SNRs as the dependent measure may be as useful as—or more useful than—behavioral studies for exploring many areas of infant cognitive development.

Finally, in Experiment 3, we investigated if SSVEPs can be used to detect infant sustained covert attention. Consistent with electrophysiological findings in adults (Toffanin et al., 2009) and infants (Richards, 2000), as well as with behavioral findings in infants (Hood, 1993), infants' SSVEP SNRs were greater for the more complex (and likely more attractive) 6×6 stimulus than the less complex (and likely less attractive) 4×4 stimulus, even when the infants were not actually fixating either stimulus. These findings extend Robertson and colleagues' (2012) results by indicating that SSVEPs might reveal *sustained* covert attention in addition to the very brief covert attention detectable just prior to gaze shifting.

The current results support the use of SSVEPs as a sensitive tool for detecting neural events that may reflect changes in overt and covert attention, a tool that can be used with few complications. Specifically, we excluded no infants due to movement artifacts; the average attrition rate was low across these three studies (8.3% of the infants were excluded due to technical malfunctions or insufficient looking). Further, the experimental procedure took less time than typical infant EEG paradigms (Stets et al., 2012). Viability of SSVEP measures in infant attention research also implies viability of related measures, such as steady-state probe topography, a possible future direction for studies examining the distribution of SSVEP-like activity across the scalp (e.g., more anterior vs. posterior). The potential applications of this tool would be extensive

as it offers an efficient as well as sensitive measure of infant attention that can be used to study several aspects of infant cognitive development. For example, these results support the possibility of using SSVEPs to detect developmental delays in attentional functioning early in life. Attentional deficits have been reported in individuals with autism spectrum disorders (Guillon, Hadjikhani, Baduel, & Rogé, 2014); specifically, eye-tracking evidence suggests that visual attention abnormalities in infancy may predict later developmental outcomes, including symptoms of autism (Jones & Klin, 2013). Thus, SSVEPs, too, may be a useful tool for detecting abnormalities in infants' overt and covert attention allocation, and could ultimately inform early interventions for at-risk infants.

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